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A unifying model for planform straightness of ripples and dunes in air and water

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ABSTRACT

Geologists, physicists, and mathematicians have studied ripples and dunes for more than a century, but despite considerable effort, no general model has been proposed to explain perhaps the most fundamental property of their morphology: why are some bedforms straight, continuous, parallel, and uniform in planform geometry (i.e. two-dimensional) whereas others are irregular (three-dimensional)? Here we argue that physical coupling along the crest of a bedform is required to produce straight crests and that along-crest flow and sand transport provide effective physical mechanisms for that coupling. Ripples and dunes with the straightest and most continuous crests include longitudinal and oblique dunes in unidirectional flows, wave ripples, dunes in reversing flows, wind ripples, and ripples migrating along a slope. At first glance, these bedforms appear quite different (ripples and dunes; air and water; transverse, oblique, and longitudinal orientations relative to the net sand-transport direction), but they all have one property in common: a process that increases the amount of along-crest sand transport (that lengthens and straightens their crests) relative to the across-crest transport (that makes them migrate and take the more typical and more three-dimensional planform geometry). In unidirectional flows that produce straight bedforms, along-crest transport of sand is caused by along-crest flow (non-transverse bedform orientation), gravitational transport along an inclined crest, or ballistic splash in air. Bedforms in reversing flows tend to be straighter than their unidirectional counterparts, because reverse transport across the bedform crest reduces the net across-crest transport (that causes the more typical irregular geometry) relative to the along-crest transport (that smoothes and straightens planform geometry).

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1. Introduction

1.1. Purpose

Most ripples and dunes are irregular in planform geometry (Fig. 1a–c), but a seemingly disparate assortment of bedforms are unusually regular (Figs. 1d–f, 4–6, and Table 1). These exceptionally two-dimensional bedforms include: (1) wind ripples, (2) bedforms that are oriented parallel or oblique to flow rather than transverse; (2) bedforms migrating along a slope, and (4) bedforms in reversing flows (waves, tides, and seasonally reversing winds). The goals of this review are to consider what these diverse bedforms have in common and thereby learn what processes control bedform straightness.

1.2. Definitions

A variety of measures have been proposed to quantify bedform two-dimensionality or the degree to which bedforms have long straight crests and troughs, constant elevation of crests and troughs, uniform spacing or wavelength, and lack of defects (Tanner, 1967; Allen, 1968a; Venditti et al., 2005a). The two-dimensional bedforms considered here (Figs. 1d–f; 4–6) are exceptionally two-dimensional —more so than most bedforms in unidirectional flows than are typically described as “two-dimensional” (Harms, 1969; Allen, 1977).

Three-dimensional structure of bedforms can be defined by a variety of geomorphic attributes including sinuous crestlines or troughs, crests or troughs with varying elevation (such as scour pits in the troughs), terminations or junctions of troughs and crests, intersecting

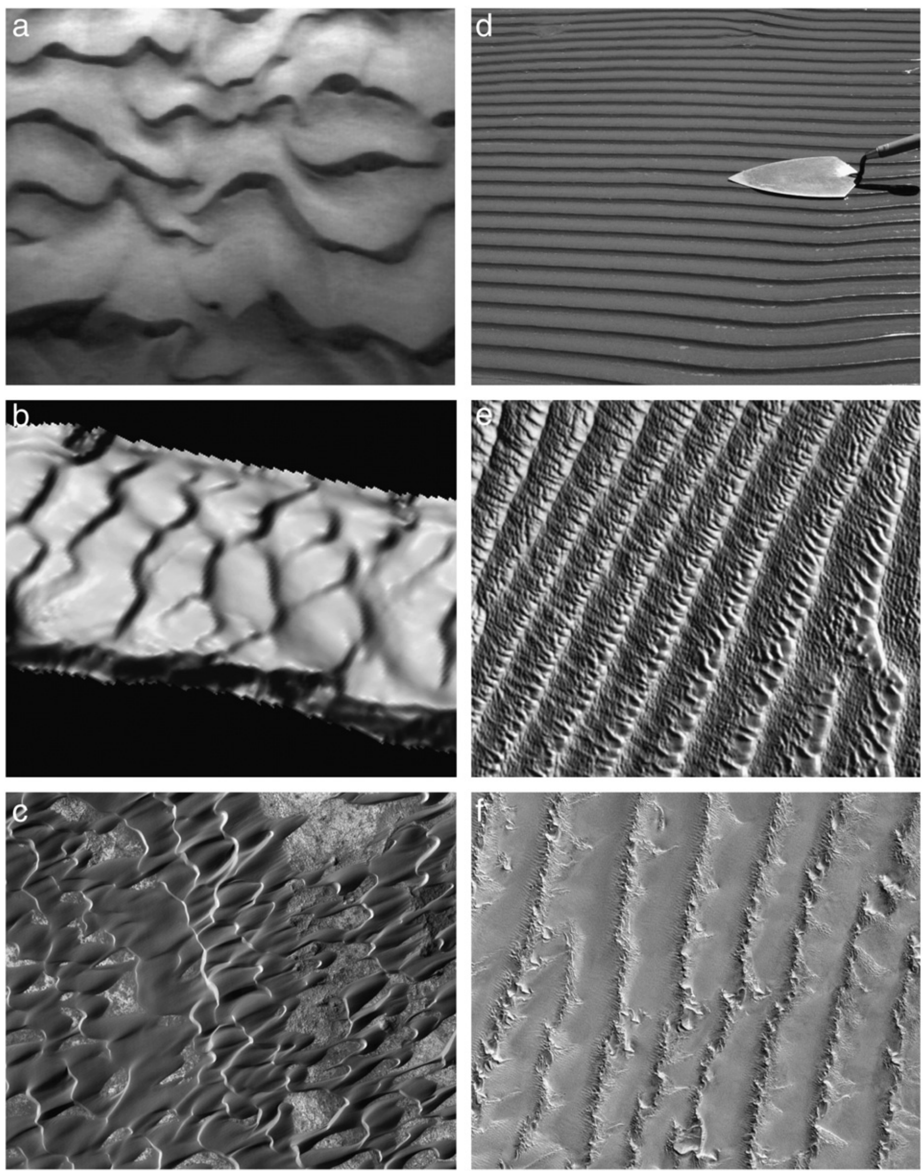

Fig. 1. Three-dimensional ripples and dunes in unidirectional flows (left column a–c) and two-dimensional ripples and dunes in reversing flows (right column d–f). (a) Ripples formed by unidirectional flow in a lab flume; flow is from top to bottom; field of view is 40 cm from right to left. (b) Dunes in unidirectional flow in the Colorado River in Grand Canyon viewed by multibeam sonar (Kaplinski et al., 2009); channel width is approximately 70 m. (c) Crescentic eolian dunes on Mars (winds roughly from right to left; field of view ~6 km × 6 km); (Image: NASA/JPL/University of Arizona; Nili Patera Ripples ESP_017762_1890). Right column shows straight-crested bedforms created by reversing flows. (d) Ripples formed by reversing wave-generated flow on a sand bar in Colorado River in Grand Canyon. (e) Dunes formed by reversing tidal currents, San Francisco Bay, California (Barnard et al., 2011); wavelength is 60 m. Superimposed dunes demonstrate along-crest sand transport (from bottom to top in image). (f) Eolian dunes formed by seasonally reversing winds, Namib Desert; dune wavelength is 2 km. Superimposed dunes demonstrate along-crest sand transport (from bottom to top in image). Landsat Earth as Art series; USGS and NASA.

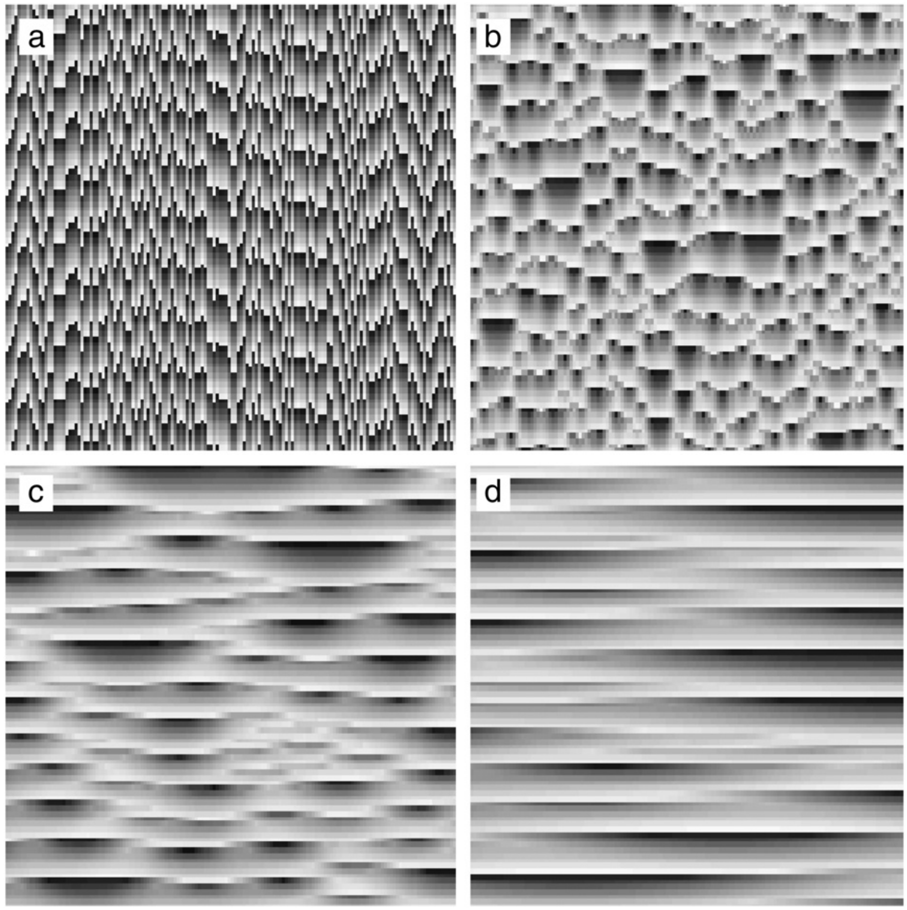

Fig. 2. Increases in along-crest coupling produce straighter synthetic ripple-like features. Images were computed using the "dripping handrail" model for spatio-temporal chaos (Crutchfield and Kaneko, 1987; Rubin, 1992). Each pixel is calculated from pixels in the row above, and can therefore be envisioned representing top-to-bottom "flow". Along any streamline, elevation (represented by brightness) gradually increases and then abruptly decreases (analogous to an upstream-downstream profile across an asymmetrical bedform). (a) Each pixel is calculated from the single pixel above; resulting "crests" have no coherence. (b–d) Each pixel is calculated from an increasing number of pixels in the row above (3, 17, and 67 in b, c, and d, respectively).

or superimposed bedforms, and lee-side spurs (which may range from superimposed bedforms to horns that are part of the main bedform). Although existing bedform-simulation models can create nearly all of these attributes individually (Rubin, 1987), no formal definition is available to quantify the degree to which a bedform may have these various properties before it is considered three-dimensional. The spatial autocorrelation of bedform topography (measured between two regions of the bed shifted in an along-crest direction) is an ideal measure of two-dimensionality because it accounts for all kinds of three-dimensional morphology. This statistical measure closely approximates the definition of two-dimensionality, although filtering or another statistical approach may be required to eliminate small superimposed bedforms. Where bedforms are perfectly two-dimensional, all profiles would be identical, and the mean autocorrelation would be equal to 1; the presence of any topographic irregularities such as bends, terminations, junctions, scour pits, or irregular crest heights would reduce the spatial autocorrelation.

1.3. Perspective

Most previous studies of bedform two-dimensionality have focused on how flow strength affects the shape of transverse ripples and dunes in unidirectional subaqueous flows (discussed in Section 3.1.3); to my knowledge, there are no previous studies that address the origin of the more extreme two-dimensionality that arises under the broad range of conditions reviewed here. In general, previous studies have taken two perspectives. One perspective is that bedforms tend to be two-dimensional until three-dimensionality is imposed by the fluid. For example, Allen (1968b, p. 170) stated that ripples become irregular in response to a "superimposed three-dimensional instability which modifies the shapes of the ripples from the two-dimensional condition of perfectly straight crests." Allen (1966, p. 182) presented this idea in more general terms:

"Since the bed forms under consideration are the products of moving water acting upon sediment in transport, it is reasonable to

Table 1
Two-dimensional bedforms and their origins.

Setting	Processes causing high rates of gross along-crest transport relative to net across-crest transport
Longitudinal and oblique bedforms in unidirectional flows	Flow and transport have an along-crest component.
Bedforms migrating along a slope (inclined crests)	Gravity drives along-crest transport.
Wind ripples	Along-crest transport caused by ballistic impacts that splash grains laterally.
Bedforms in reversing flows	Flow reversals reduce net across-crest transport, but allow along-crest transport.

expect that the geometry of the forms will depend on and reflect the flow-vector fields present in the water. The discussion above, drawing on observational work and the principles of fluid flow, suggests that this conclusion is justified. Thus it was shown that two-dimensional bed forms are associated with two-dimensional flow-vector fields in the flows. Three-dimensional bed forms were suggested to be the products of three-dimensional flow systems."

Although the simplicity of this idea is appealing, it conflicts with observations detailed below. The alternative perspective is that flows and bedforms are characteristically three-dimensional, but that some flow conditions can induce two-dimensionality.

That second perspective is adopted here, for the following reasons. First, as noted by Gyr and colleagues (Gyr and Kinzelbach, 2004; Gyr and Hoyer, 2006), the flows under which sediment transport is initiated are three-dimensional rather than two-dimensional; under very weak flows that transport sand, the bed takes the form of longitudinal sand stripes or parting lineations. In other words, flows are three-dimensional even in some flows too weak to form ripples. Second, transverse subaqueous bedforms in unidirectional flows are generally three-dimensional rather than two-dimensional (Fig. 1a–c). Allen (1966, p. 182) stated "Relatively few types of bed form are two-dimensional"; Middleton and Southard (1984) reported that even the straightest subaqueous ripples in unidirectional flows are less than ideally two-dimensional; and Costello and Southard (1981, p. 855) stated "all of our two-dimensional forms show at least some deviation from the ideally straight and even crests and troughs, and are therefore quasi-three-dimensional or mildly three-dimensional according to Allen's classification". Third, lab experiments moving an artificial two-dimensional transverse bedform on a rigid plate through standing water (Reffet et al., 2010, Fig. 4c) show that the bedform quickly becomes three-dimensional even in this situation where the flow has no inherent three-dimensional structure (because the flow has no motion whatsoever other than that induced by motion of the bed). Given these observations that sand-transporting flows and bedforms both tend to be three-dimensional, special processes are inferred to be necessary to cause two-dimensionality; identifying those special processes is the focus of this paper.

2. Theory and approach

2.1. Straightness requires along-crest coupling

In unidirectional flows, bedforms generally have crescentic, barchanoid, or irregular planform geometry (Bagnold, 1941; Allen, 1966; Middleton and Southard, 1984; Baas, 1994; Venditti et al., 2005a; Reffet et al., 2010), and we hypothesize that two-dimensionality arises in situations where along-crest coupling processes are strong enough to overcome that tendency for three-dimensionality. For a ripple or dune to have a straight continuous crest, some physical mechanism must operate to couple the topography at different along-crest locations. Without such coupling, different sites along a crest need not remain locked in phase and are free to form breaks, bends, or junctions. Hypothetically, if flow and topography along every streamline were completely decoupled from adjacent streamlines, "bedform" crests would be randomly phased from one streamline to another, and coherent bedforms could not exist (Fig. 2a). In nature, such complete decoupling is physically impossible, because it would require vertical slopes on the bed and infinite shear between adjacent streamlines. In numerical experiments, increasing the amount of lateral coupling produces bedform-like structures with straighter and more continuous crests (Fig. 2b–d). As expected, as these computed structures become more two-dimensional, the spatial autocorrelation increases (Fig. 3).

A wide variety of processes can cause along-crest coupling of flow and/or sediment transport. Coupling between adjacent streamlines can be caused by: flow induced by surface waves (Kennedy, 1969); vortices and interactions between vortices (Gyr and Kinzelbach, 2004; Gyr and Hoyer, 2006); changes through time in the local flow due to upstream topography; along-crest diffusion of topography driven by saltation or gravity (Hersen, 2004); and along-crest flow and sand transport, which is enhanced by lee-side flow deflected by the bedform crest (Allen, 1968a; Tsoar, 1983; Dietrich and Smith, 1984; Sieben and Talmon, 2011). These processes have been called "lateral coupling" (Hersen, 2004), "sidewise coupling" (Gyr and Kinzelbach, 2004), "diffusion in the transverse direction" (Yizhaq et al., 2004), and "phase locked" (Gyr and Schmid, 1989; Venditti et al., 2005a). Here we generalize these processes and use the term "along-crest coupling" to specifically include situations where bedforms are oblique to flow and where coupling therefore might be oblique to flow rather than "lateral" or "sidewise" with respect to the generalized flow direction. Regardless of what these processes are called, coherent bedform crests cannot exist without them, and every model that produces bedforms with coherent crests incorporates such processes, whether explicitly stated (Yizhaq et al., 2004) or not. Increasing the amount of coupling in models produces broader and smoother features—not just in toy models of dripping handrails (Figs. 2–3) but also in more sophisticated models of dunes (Hersen, 2004).

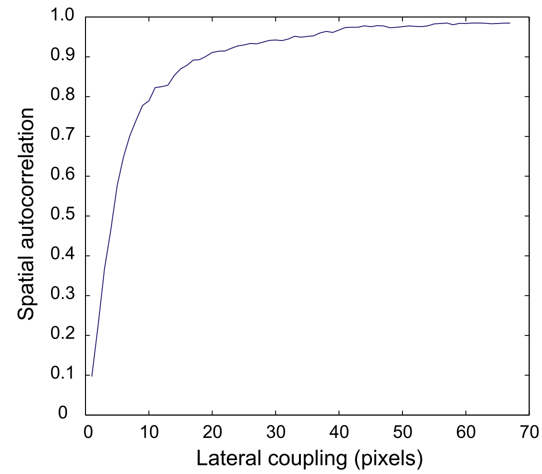

Fig. 3. Spatial autocorrelation of structures computed using the model in Fig. 2. As the along-crest coupling increases from 1 pixel to 67 pixels, autocorrelation (measured between plaquettes shifted 6 pixels laterally) increases. This increase in autocorrelation quantifies what is visible in Fig. 3: increased coupling produces more two-dimensional structures. This plot also demonstrates how spatial autocorrelation can be used to quantify two-dimensionality.

2.2. Causes of along-crest coupling

The fundamental principle explored in this paper is that all bedforms require at least some along-crest coupling to have coherent crests, and exceptionally two-dimensional bedforms require unusually great along-crest coupling. In flows that are nominally unidirectional, along-crest coupling might arise either from systematic along-crest flow or sediment transport, or from directional variability due to turbulence or other processes that cause intermittent along-crest flow or sediment transport. Examples of such processes are discussed in Section 3.1.

The situation is more complicated in reversing flows. The approach taken here is to resolve sand transport into across-crest and along-crest components (Rubin and Hunter, 1985). Ripples and dunes generally form with a transverse orientation in unidirectional flows (Bagnold, 1941; Rubin and Hunter, 1987; Rubin and Ikeda, 1990; Werner and Kocurek, 1997; Reffet et al., 2010), so the net across-crest component of transport is taken as the transport that generates characteristic irregular crescentic or barchanoid morphology. In contrast, transport that parallels the mean bedform orientation is treated as the process that couples, smoothes, and straightens that morphology. That transport L is given by

$$L = \frac{\sum_{\alpha=0}^{2\pi} |\cos(\omega-\alpha)(Q_\alpha)|}{\sum_{\alpha=0}^{2\pi} |Q_\alpha|} \quad (1)$$

where ω is bedform orientation, and Q_α represents the magnitude of sand transport toward each direction α from 0 to 2π. Because along-crest transport couples adjacent locations when the transport is toward either of the two along-crest directions, along-crest transport is summed regardless of sign of direction of transport. The denominator in Eq. (1) represents total transport, so L is equal to net along-crest transport normalized relative to total transport and is therefore dimensionless.

The magnitude of the sand-transport process that tends to create the characteristic barchanoid or other irregular planform geometries (C, sand transport in the across-crest direction normalized relative to total transport) is given by

$$C = \frac{\left|\sum_{\alpha=0}^{2\pi} \sin(\omega-\alpha)(Q_\alpha)\right|}{\sum_{\alpha=0}^{2\pi} |Q_\alpha|} \quad (2)$$

Transport in the reverse direction across a crest reduces the rate of bedform migration, so the sign of transport is considered in Eq. (2), with the sum defined to be positive in the direction of migration.

The ratio of L to C is S, a dimensionless measure of the importance of straightening processes for a specified sequence of sand-transport vectors

$$S = \frac{L}{C} = \frac{\sum_{\alpha=0}^{2\pi} |\cos(\omega-\alpha)(Q_\alpha)|}{\left|\sum_{\alpha=0}^{2\pi} \sin(\omega-\alpha)Q_\alpha\right|} \quad (3)$$

Eq. (3) illustrates the two ways that a large value of S can arise in reversing flows. First, where reversing flows across a bedform transport nearly equal quantities of sand—as in the case of many wave ripples—C approaches zero, and S approaches infinity. Second, where both transport directions are not exactly perpendicular to the bedform crest, at least one of the flows must transport sand along-crest, which increases the numerator L.

3. Results and discussion

3.1. Two-dimensionality in unidirectional flows

3.1.1. Wind ripples

Wind ripples (Fig. 4) are generally more two-dimensional than subaqueous ripples in unidirectional flows (Tanner, 1967). Here it is hypothesized that wind ripples are more two-dimensional because of along-crest coupling resulting from ballistic grain impacts that eject grains laterally across streamlines. Including such lateral diffusion in models is necessary to generate simulated ripples that are spatially uniform (Yizhaq et al., 2004).

Although the two-dimensional splash function "is currently not known, either from experiments or theory" (Yizhaq et al., 2004, p. 211), ballistic transport across streamlines can be expected to be considerably more important for ripple-producing flows in air than in water. We can quantify the importance of ballistic transport using a particle Reynolds number (approximated here by the dimensionless product of a grain's density, speed, and diameter divided by the dynamic viscosity of the fluid). In air, grain velocities are higher and viscosity is lower, resulting in particle Reynolds numbers that are 2–3 orders of magnitude larger. Greater lateral bouncing of grains at this higher particle Reynolds number can explain greater along-crest coupling.

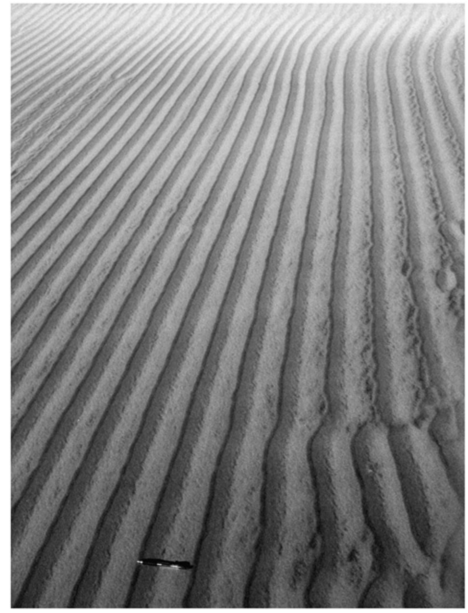

Fig. 4. Two-dimensional wind ripples in Death Valley, California; pen is approximately 15 cm. Photo by Ryan Ewing.

Although eolian ripples that form transverse to flow are generally straighter than corresponding subaqueous ripples, transverse eolian dunes in unidirectional flow are not straight. This difference may arise from the scale of the grain hop distance relative to bedform wavelength (grain hops are large relative to the wavelength of eolian ripples but small relative to dunes).

3.1.2. Oblique bedforms

A simple mechanism of along-crest coupling occurs where bedform crests are oblique or parallel to a unidirectional flow (Fig. 5). Along-crest flow and transport provide coupling and also provide a mechanism for extending bedforms in the along-crest direction (Bagnold, 1941; Allen, 1968a; Tsoar, 1983; Dietrich and Smith, 1984; Sieben and Talmon, 2011). The along-crest flow has the capability of reducing along-crest topographic irregularities by filling downwind concavities, flattening downwind convexities, or straightening bedforms by systematic migration of defects (Werner and Kocurek, 1999). The model presented here does not specifically address defect behavior, but nevertheless begins to address bedform straightening in the non-transverse cases that are recognized as more complicated (Werner and Kocurek, 1999).

Although bedforms in unidirectional flow tend to form with a transverse orientation, oblique and longitudinal orientations can arise in unidirectional flows where conditions vary temporally or spatially: where conditions vary laterally so that one region of a bedform crest outruns other regions (Fig. 5a–b), where bedform orientation is controlled by orientation of a sediment source (source-bordering dunes), where a flow changes to a new direction (either through time or with distance downcurrent) more rapidly than bedforms can re-orient, or where sand accumulates in the lee of an obstacle as "sand shadow" or "lee dunes" (Fig. 5c).

Bedforms also tend to be relatively straight where they migrate along a slope (Fig. 6); in this case, along-crest transport of sand is driven by gravity rather than flow. In addition to experiencing along-crest transport, inclined crests that are not perfectly straight are less stable than straight crests, because the local slope on sinuous bedforms must include sites that are over-steepened and under-steepened relative to

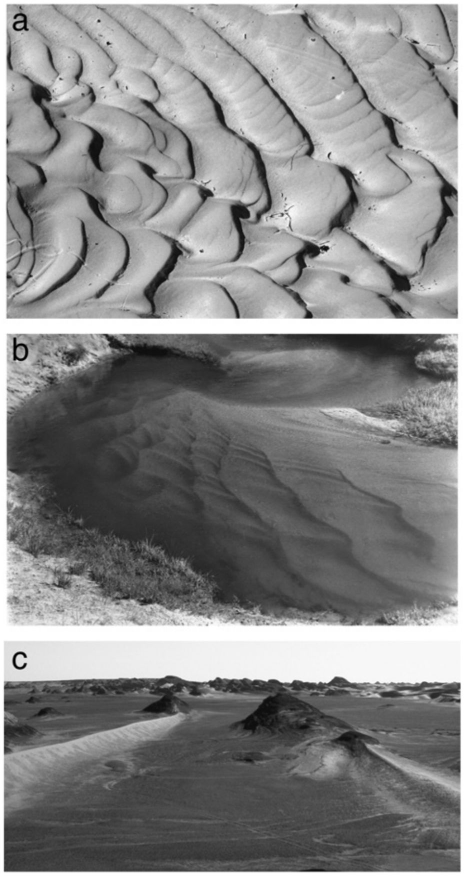

Fig. 5. Two-dimensional bedforms that have along-crest sand transport in unidirectional flows. (a) Subaqueous ripples in Harris Wash, Utah. Ripples are three-dimensional where they are transverse to flow (lower left), but near the bank (upper right) the ripples are oblique to flow—presumably because they rotated as a result of slower migration in weaker flow along the bank; wavelength is approximately 10–20 cm. (b) Subaqueous dunes oriented obliquely to flow as they migrate around a bend in Muddy Creek, Wyoming (Rubin, 1987; photo by Bill Dietrich). Flow is from lower right to top left. (c) Sand-shadow dune or lee dune aligned parallel to wind in Qaidam Basin, China (Rubin and Hesp, 2009); flow is toward the viewer; dune height is approximately 10 m.

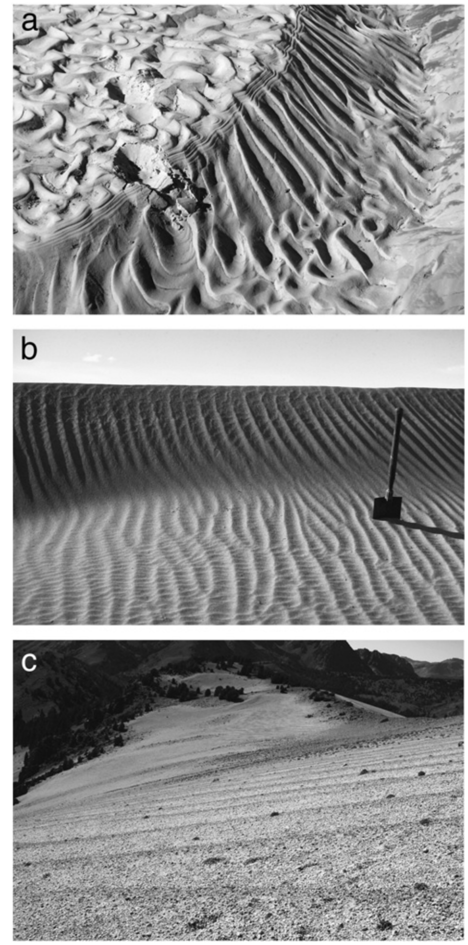

Fig. 6. Bedforms with two-dimensionality caused by gravity-driven along-crest transport. (a) Subaqeuous ripples migrating along the lee side of a bar in Harris Wash, Utah; footprint for scale. (b) Wind ripples are straighter where the slope is steeper (upper part of photo, nearer the crest on the lee side of a dune); photo by Ralph Hunter. (c) Two-dimensional eolian megaripples in pumice on a slope near Mammoth, California; scale indicated by footprints. Photo by Ryan Ewing, who confirmed (personal communication) that the megaripples on the slope were more two-dimensional than other megaripples in the area.

straight-crested bedforms, thereby resulting in an active straightening process. Although the effect of regional slope on shape of ripples has not been quantified, the effect of gravity-driven along-crest transport on ripple orientation has been measured (Howard, 1977).

Edwards et al. (1983) described unusually straight-crested ripples from Permian point-bar deposits. They reported (p. 1269) "The unusual dominance of straight-crested ripples, rather than the more common three-dimensional forms, such as linguoid ripples, may also be in some way related to flow over a transversely sloping bed…" The ripples were also oblique to flow, so the relative importance of flow obliquity and gravity in causing along-crest transport and two-dimensionality cannot be determined.

3.1.3. Subaqueous ripples and dunes

Perhaps the greatest efforts to understand bedform two- and three-dimensionality have been directed at transverse ripples and dunes in unidirectional subaqueous flows. Some of these studies have concluded that two-dimensional dunes are formed by weaker flows (Dalrymple et al., 1978; Southard and Boguchwal, 1990; Dalrymple and Rhodes, 1995), but other studies have reported that given enough time even the weaker flows produce three-dimensional dunes (Venditti et al., 2005a). Similarly, in the case of ripples in unidirectional subaqueous flows, some studies have concluded that three-dimensionality is caused by stronger flows (Allen, 1969; Harms, 1969; Banks and Collinson, 1975), whereas later studies have concluded that ripples evolve to become three-dimensional even in weak flows (Middleton and Southard, 1984; Baas, 1994).

Although the unidirectional flow conditions that create two- and three-dimensional ripples and dunes have been studied extensively, details of the precise flow processes that cause two-dimensionality are less clear—at least to this author—than the other causes of two-dimensionality reviewed in this paper. Each of the other causes has a clearly visible process that causes along-crest flow or sand transport (ballistic grain splash; along-crest transport due to gravity or flow obliquity; and processes described by Eq. (3)). In contrast, two-dimensionality in unidirectional subaqueous flows is an inextricable interaction between flow, sediment transport, and topography. Such interactions have been described as "chicken-or-egg problems" (Costello and Southard, 1981) or "self organization" (Gyr and Kinzelbach, 2004; Gyr and Hoyer, 2006). In any case, Gyr and colleagues must be correct that some such interaction between flow and topography causes two-dimensionality, even if the details are more complicated and iterative.

3.2. Two-dimensionality in bi-directional flows

To predict bedform straightness for a given alternating pair of sand-transport directions requires three steps. The first step is to calculate bedform orientation for the two specified directional modes

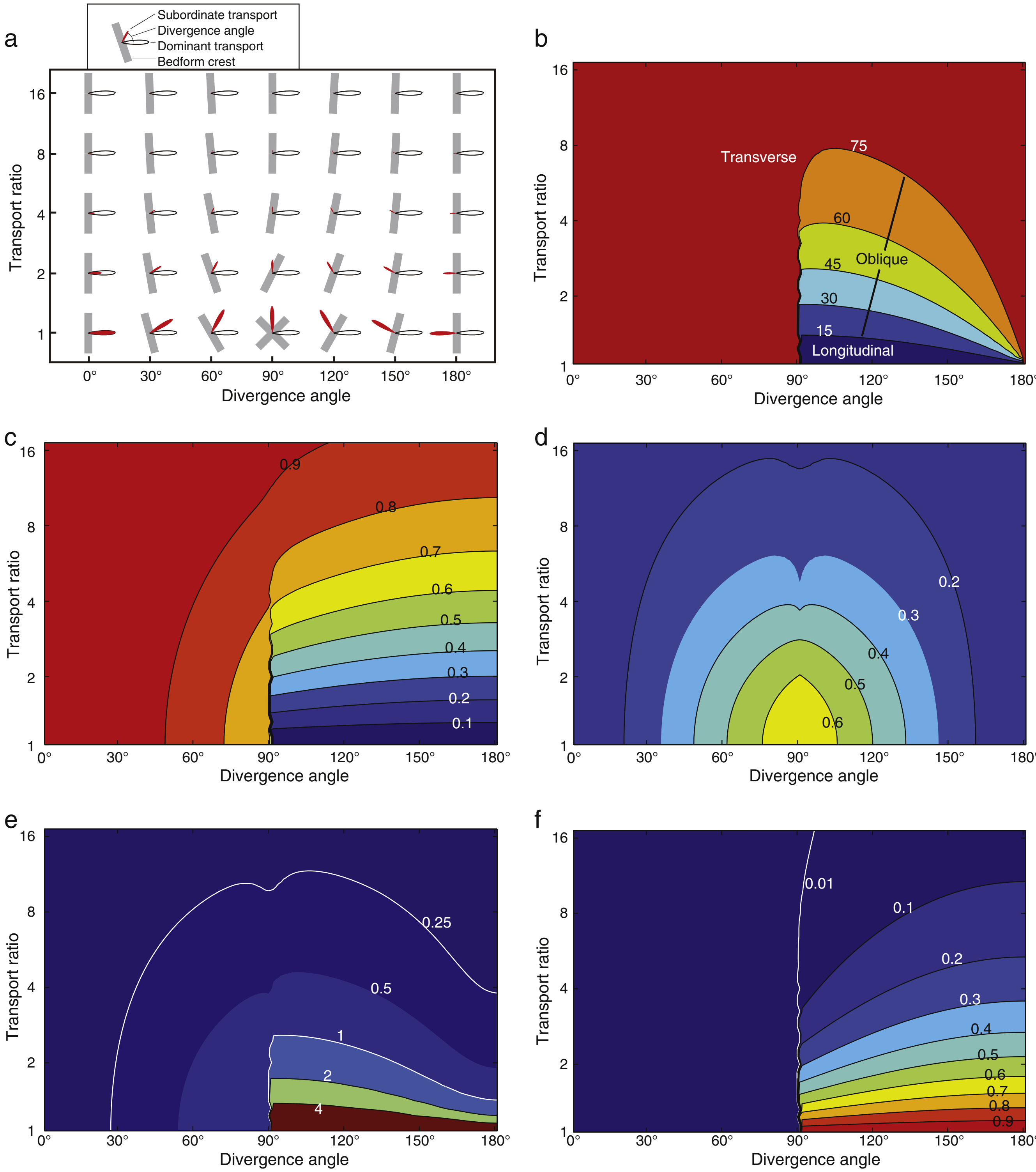

Fig. 7. Computed bedform and sand-transport properties in flows with two alternating directional modes. Plots a–f all have the same coordinate system and show bedform and sand-transport properties plotted as a function of the angle between the two directional modes (divergence angle) and their relative magnitude (transport ratio). Conditions that are calculated to have high values of S coincide with the conditions that create straight bedforms (wave ripples, tidal dunes, linear eolian dunes). (a) Definition sketch and directional plots illustrating 35 of the 7421 pairs of flows used to compute each plot in b–f. Each of these 35 plots shows a circular histogram of transport for the dominant and subordinate transport modes and the trend of the bedform calculated to arise for each pair of flows. Bedform orientation is calculated to be the trend that has the maximum gross across-crest transport (Rubin and Hunter, 1987). (b) Contour plot showing calculated orientation of bedforms relative to the resultant transport direction for each pair of flows specified by the axes. By definition, orientations range from 0° to 15° for longitudinal bedforms, 15° to 75° for oblique bedforms, and 75° to 90° for transverse bedforms. (c) Contour plot showing the ratio of net across-crest transport to total transport (C defined by Eq. (2)) as a function of divergence angle and transport ratio. Net across-crest transport approaches zero where the transport ratio is 1 and the divergence angle is between 90° and 180° (lower right region of plot). Under these conditions, across-crest transport is symmetrical. (d) Contour plot of gross along-crest transport relative to total transport (L defined by Eq. (1)). Where along-crest transport approaches or exceeds half of all transport (center bottom), two sets of intersecting bedforms have been reported, as discussed in the text. (e) Contour plot of gross along-crest transport relative to net across-crest transport (ratio of values in Fig. 7c to d as defined by S in Eq. (3)). Straight bedforms are predicted to occur where S is large. Values are contoured on a log scale. (f) Contour plot showing symmetry of across-crest transport (ratio of transport causing reverse migration to transport causing migration in the dominant direction). Transport across crests is symmetrical in the lower right of plot, in roughly the same region as where S is large in Fig. 5e. In other words, bedforms that are symmetrical in cross-section are predicted to form under the same conditions that produce two-dimensional bedforms (with qualifications discussed in text).

(Fig. 7a–b) by solving for the orientation subject to the maximum gross bedform-normal transport, an approach developed by Rubin and Hunter (1987) and confirmed by additional experiments (Rubin and Ikeda, 1990; Reffet et al., 2010), field observations (Dalrymple and Rhodes, 1995; Lancaster, 2010), and computations (Werner and Kocurek, 1997; Parteli et al., 2009). For this approach to be meaningful, the individual pulses of transport toward each direction must be small enough to not modify the bedforms substantially, so that a single bedform orientation arises from flow pulses toward both directions. The second step is to compute net across-crest transport (Eq. (2), Fig. 7c) and gross along-crest transport (Eq. (1), Fig. 7d) for the calculated orientation and specified flows. Finally, S is computed by taking the ratio of those values (Eq. (3), Fig. 7e). Bedform orientation and S were thus calculated for 7421 bi-directional flows with the ratio of transport toward the two directional modes varying from 1 to 16 and the angle between those two modes varying from 0° to 180°.

Previous experiments and computations of bedform orientation in bi-directional flows utilized two nominally unidirectional flows (Rubin and Hunter, 1987; Werner and Kocurek, 1997; Reffet et al., 2010), but computations here impose a small spread in directional variability to each mode (Fig. 7a). Such a directional spread in a natural flow might result from fluctuations in flow direction external to the bedform boundary layer or from the passage of vortices or other flow structures formed by the interacting flow and bed. Lab experiments show that downstream from an artificial sand mound, bedforms spread laterally (Southard and Dingler, 1971), and measurements from photographs of Venditti et al. (2005b, Fig. 4) suggest that the angle of spread for ripple-producing flows is approximately $\pm 15°$ from directly downstream. The computations here use a spread having a normal distribution with a standard deviation of 10°, so that approximately 87% of all transport occurs within $\pm 15°$ of downstream. This sets the distribution of transport directions in nominally unidirectional flows, but the calculated results are not particularly sensitive to the directional variability chosen. Imposing a different value changes the predicted values of S, but the maximum values always occur where the two transport modes are equal in magnitude and the angle between them is between 90° and 180° (i.e., reversing flows at the lower right in Fig. 7).

The results in Fig. 7e predict that the highest values of S occur in reversing flows where the two flows are equal in magnitude and where the angle between the two modes is between 90° and 180° (right side of the bottom edge of Fig. 7e). The model proposed here suggests that these are the conditions that produce straight bedforms. Because the same conditions produce symmetrical transport back and forth across the crest (i.e., symmetry of across-crest transport = 1, as occurs at the lower right in Fig. 7f), these bedforms are also symmetrical in cross-section. In other words, the predictions suggest that symmetrical bedforms and straight bedforms both are created by reversing flows represented in the lower right in Fig. 7.

These predictions are consistent with observations. For example, wave ripples are typically straighter than ripples in unidirectional flows (Tanner, 1967; Harms, 1969). Similarly, the relatively straight eolian dunes known as “linear dunes” or “self dunes” (from Arabic for “sword”) form in seasonally reversing winds (Bagnold, 1941; Lancaster, 1982).

Eq. (3) and Fig. 7 suggest that tidal dunes in flows with equal ebb and flood flows also should be straight-crested, but data are not available to test this hypothesis, because studies have not evaluated straightness as a function of flow properties considered here to be important. Some tidal dunes are, however, exceptionally straight (Fig. 1e). Other tidal dunes have crests that are relatively continuous, but with scour pits in their troughs. Regarding such tidal bedforms, Dalrymple and Rhodes (1995) suggested: “the presence of reversing flow causes these bedforms to be more continuous than those in unidirectional (fluvial) flow, but comparative data are lacking”. Lee et al. (2006) show an example of exceptionally straight tidal dunes formed in flows with such equal ebb and flood transport that the dunes have little or no detectable migration (near the lower right corner of Fig. 7). It is notable that the particularly straight tidal dunes and linear eolian dunes in Fig. 1e–f both have superimposed dunes indicating along-crest transport.

At least one set of lab experiments supports the idea proposed here that directional properties of a flow can determine whether bedforms are two-dimensional or three-dimensional, independently of any two- or three-dimensional structure in the flow. When Reffet et al. (2010) moved a sand-covered plate in a narrow range of directions through standing water, they created barchanoid bedforms with a transverse orientation, but when they moved the plate alternately in two directions separated by 135° or 172°, they created straight-crested bedforms with a longitudinal orientation. Because the flow external to the bedform boundary layer was identical (standing water) in the two cases, the three-dimensional of the bedforms in unidirectional flow could not have been due to Allen's “superimposed three-dimensional instability” intrinsic to the flow. Instead, the longitudinal bedforms must have become straighter due to the pair of alternating oblique flows, which is consistent with the resulting relative increase in along-crest transport described by Eq. (3).

3.3. Complications due to intersecting bedforms

Although bi-directional flows with a transport ratio of 1 and a divergence angle of roughly 90° have a high value of S, these flows have an additional complication that might inhibit formation of straight simple bedforms. Under such conditions, two bedform orientations (transverse and longitudinal) are almost equally stable because they have nearly equal gross across-crest transport, resulting in formation of intersecting bedforms, as has been observed in the field (Dalrymple and Rhodes, 1995), modeled in computations (Werner and Kocurek, 1997), and created in the lab (Reffet et al., 2010). These previous studies have shown that the conditions that favor formation of intersecting bedforms are centered in the area in Fig. 7c where along-crest transport is greatest.

3.4. Complications due to superimposed bedforms

In the 1960s and 1970s, it was shown that different kinds of bedforms originated under mutually exclusive hydraulic conditions, so it was puzzling that one kind of bedform could occur superimposed on another. Allen (1978) explained this paradox as arising from time-varying flows, with the smaller superimposed bedforms forming in new flow conditions while the larger bedforms were the remnant of prior flow conditions. In contrast, Rubin and McCulloch (1980) argued that large bedforms create internal boundary layers in which small bedforms can form, even in steady flows. The small bedforms can be a different kind (such as ripples superimposed on dunes) because the internal boundary layer has a different flow thickness and strength. Superimposed bedforms also commonly migrate in a different direction from the main bedforms (Brookfield, 1977; Figs. 1e–f, 5a this paper), because the internal boundary layer that creates the superimposed bedforms can differ in flow direction or because one region of the superimposed bedform outruns another, thereby causing a rotation in orientation. Similarly, it can be expected that superimposed bedforms might be more or less two-dimensional than the main bedforms, depending on inclination of the surface over which the superimposed bedforms migrate, orientation of the superimposed bedforms relative to one or more boundary-layer flow directions modified by the topography of the main bedform, and changes caused where the superimposed bedforms experience differing local flow conditions on the surface of the main bedforms.

Eventually it may be possible to define an arbitrary sequence of flow vectors, predict the geometry of the main bedforms that arise from that sequence, model the local boundary layer created by the interaction of that topography with the external flow, and predict the morphology and motion of superimposed bedforms within that boundary layer. Until then, we can still use orientation and migration of superimposed bedforms as an indicator of near-bed flow and sand transport (Brookfield, 1977). For example, oblique orientation of the main bedforms can be inferred where the main bedform migrates laterally (or is asymmetrical in cross-section) while superimposed bedforms migrate in a preferential along-crest direction (Rubin and Hunter, 1985; Rubin, 1987).

3.5. Unresolved issues

The results presented here do not address a number of processes that might influence planform geometry, including: (1) intersection of two or more sets of bedforms such as those that form in bi-directional flows diverging by ~90° (Dalrymple and Rhodes, 1995; Werner and Kocurek, 1997; Reffet et al., 2010), (2) formation of superimposed bedforms that become so large that they effect the planform geometry of the main bedforms (as Brookfield, 1977 showed for cross-sectional geometry), (3) formation of bedforms in flows with three or more vectors, such as combined waves and currents (Lacy et al., 2007) or intersecting sets of waves, (4) formation of bedforms in flows with directional modes that individually transport enough sand to substantially alter bedform morphology, such as small dunes that Rubin and Ikeda (1990) avoided due to this complication, and (5) sorting of sediment by grain size into patches of sediment that respond differently to flow. Nevertheless, the model presented here identifies the unifying underlying process that causes two-dimensionality in a wide variety of diverse situations.

4. Conclusions

Coherent bedform crests cannot exist without along-crest coupling, and bedforms with particularly straight crests are inferred to arise from greater coupling. A wide variety of natural bedforms have unusually straight crests: ripples in oscillatory flow, dunes in reversing tidal flows, eolian dunes in seasonally reversing winds, longitudinal and oblique dunes in air and water, ripples migrating across a slope, and wind ripples. Each of these kinds of bedforms originates in a setting with a process that increases the proportion of along-crest transport relative to the net across-crest transport (transport that makes the bedforms migrate and produces more typical irregular planform geometry). In unidirectional flows that produce straight bedforms, along-crest transport of sand is caused by along-crest flow (non-transverse bedform orientation), gravitational transport, or ballistic splash. Bedforms in reversing flows are straighter than their unidirectional counterparts, because reverse transport across the bedform crest reduces the net across-crest transport (that causes the more typical irregular geometry) relative to the along-crest transport (that smoothes and straightens planform geometry). Considerable effort has previously been directed at quantifying the conditions under which subaqueous transverse ripples and dunes in unidirectional flow are two- or three-dimensional, but the results are not necessarily applicable to situations where bedforms are oblique to flow, have inclined crests, or occur in directionally varying flows.

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